ChinaFlux Day 1

Hayden Mahan

CAMPBELL SCIENTIFIC

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Topics

- Definition and explanation of the boundary layer
- Boundary layer fluid characteristics: turbulence
- Continuity Equation
- Reynolds Decomposition

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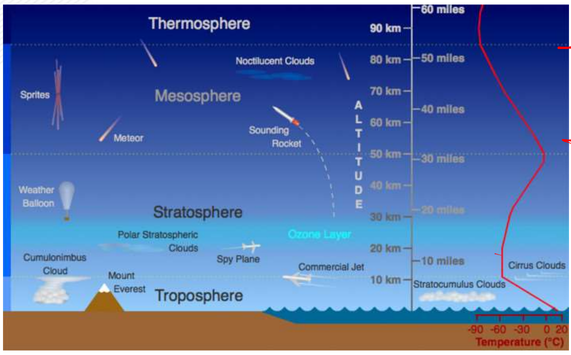
Layers of the Earth's Atmosphere



- Troposphere: Nearly all weather occurs here; 99% of the water vapor in the atmosphere is here; the boundary layer resides in this part of the atmosphere
- Stratosphere: Ozone layer; Ozone molecules in this layer absorb high-energy ultraviolet (UV) radiation from the Sun, converting the UV energy into heat; lacks the turbulence and updrafts of the troposphere; commercial passenger jets fly in the lower stratosphere; the jet stream flows near the border between the troposphere and the stratosphere
- Mesosphere: Most meteors burn up here; the coldest temperatures in Earth's atmosphere, about -90° C (-130° F), are found near the top of this layer; air pressure at the bottom of the layer is well below 1% of the pressure at sea level
- Thermosphere: Sun's high-energy X-rays and UV are absorbed raising temps between 500° C (932° F) to 2,000° C (3,632° F); the air in this layer is so thin that it would still feel freezing cold to us; satellites orbit Earth; Variations in the amount of energy coming from the Sun vary the height of the top layer between 500 and 1,000 km (311 to 621 miles) above the ground; the aurora, Northern/Southern Lights occur here

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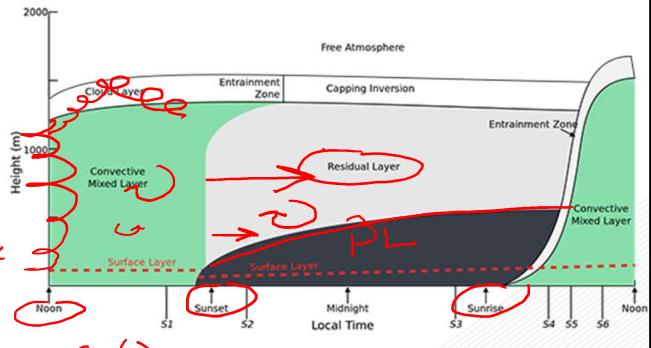
Atmospheric Boundary Layer (ABL)

- The bottom layer of the troposphere in contact with Earth's surface
- Turbulent and capped by a statically stable layer of air or temperature inversion
- The depth varies in time/space
  - Ranging from 10s m in strongly statically stable situations, to several km in convective desert conditions
- During fair weather over land, the ABL has a marked diurnal cycle
  - Daytime: mixed layer of strong turbulence grows in depth, capped by a statically stable entrainment zone of varying turbulence
  - Sunset: turbulence decays, leaving a residual layer in place of the mixed layer
  - Nighttime: the bottom of the residual layer is transformed into a statically stable boundary layer by contact with the radiatively cooled surface
- Cumulus and stratocumulus clouds can form within the top portion of a humid ABL, while fog can form at the bottom of a stable boundary layer.
- The bottom 10% of the ABL is called the surface layer.



Atmospheric Boundary Layer

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Atmospheric Boundary Layer

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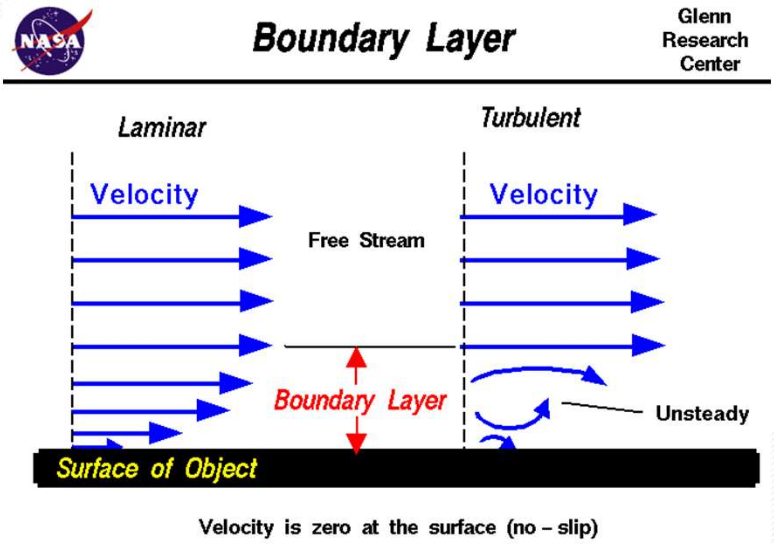
Boundary Layer Characteristics



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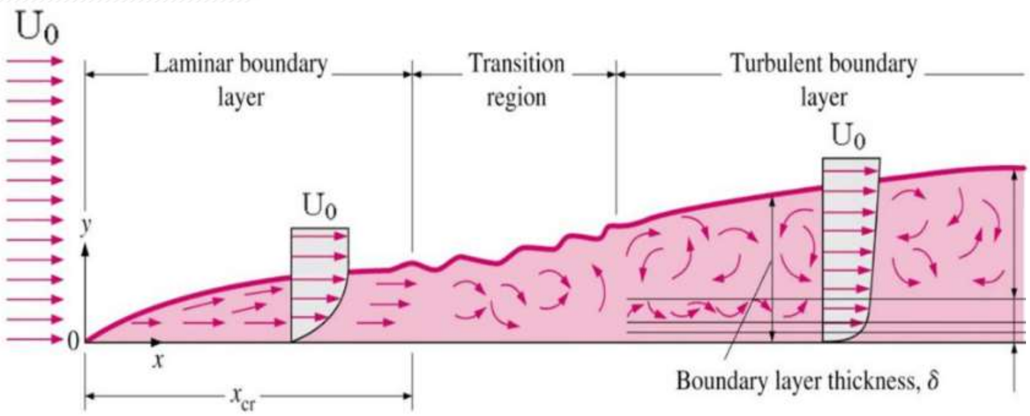
Boundary Layer Characteristics



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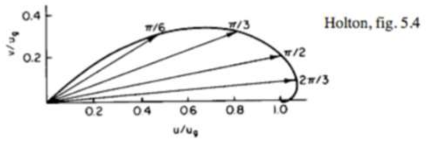
HM1

Boundary Layer Characteristics



Holton, fig. 5.4

Fig. 5.4 Hodograph of the wind components in the Ekman spiral solution. The arrows show the velocity vectors for several levels in the Ekman layer, while the spiral curve traces out the velocity variation as a function of height. Points labeled on the spiral show the values of γz, which is a nondimensional measure of height.

Archetypal shear flows

Tritton

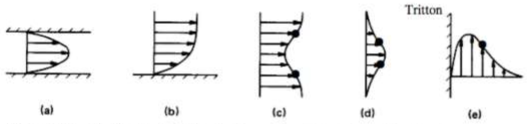
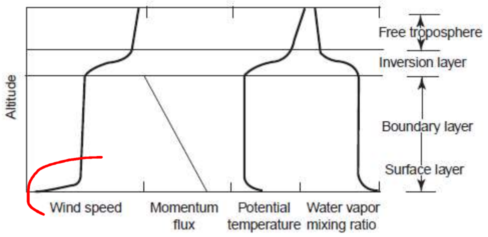


Figure 17.13 To illustrate that the velocity profiles of (a) pipe flow, (b) a boundary layer, (c) a wake, (d) a jet, and (e) a free convection boundary layer are all shear flows.

Boundary Layer Characteristics



Geernaert 2003

- Wind speed goes to 0 near the surface
- Momentum flux decreases with height as turbulence decreases
- Potential Temperature and water vapor mixing ratio decrease near the surface and then remain uniform until reaching the capping inversion

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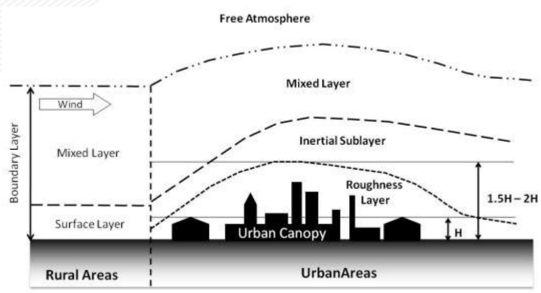
HM1 Consider removing this slide
Hayden Mahan, 8/18/2021

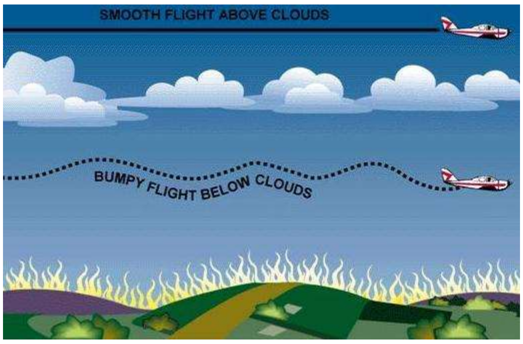
Surface Layer



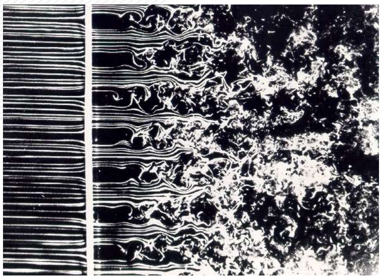
After Muller [5]

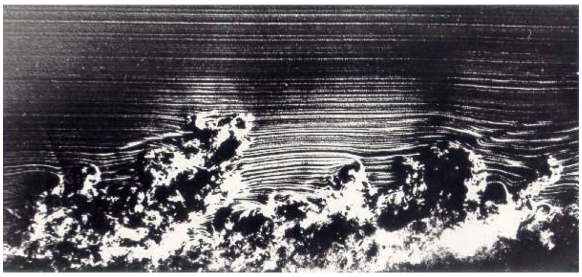
- Surface Layer (Lowest 10% of the ABL)
  - Inertial sublayer
  - Roughness Layer
- The surface influences the atmosphere in three main ways
  - Sensible heat flux
  - Moisture flux from the surface to the atmosphere
  - Radiation

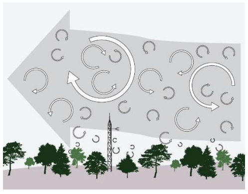
Turbulence… it's, well… randomness… sort of



Turbulence







Turbulence is quasi-chaotic motion of swirling parcels of air called eddies. Caused by surface forcings (solar heating, wind shears from frictional drag, and turbulent wakes from obstacles and uneven terrain).

If surface forcings are insufficient, flow will be laminar.

Turbulence is orders of magnitude more efficient at mixing than diffusion. (Stull, 1988)

http://fdrc.iit.edu/research/images/

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Turbulence

- Turbulence is important because it mixes and churns the atmosphere and distributes water vapor, smoke, energy, etc. vertically and horizontally.
- Atmospheric turbulence near the Earth's surface differs from that at higher levels.
  – At low levels (~1-3 km), turbulence has a marked diurnal variation under partly cloudy and sunny skies, reaching a maximum about midday.
  – At high levels, frictional effects greatly reduce, eliminating most small-scale turbulence characteristics. Although upper-level winds are usually relatively regular, they sometimes become turbulent enough to affect aviation.

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Turbulence Generation

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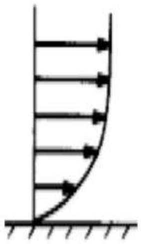
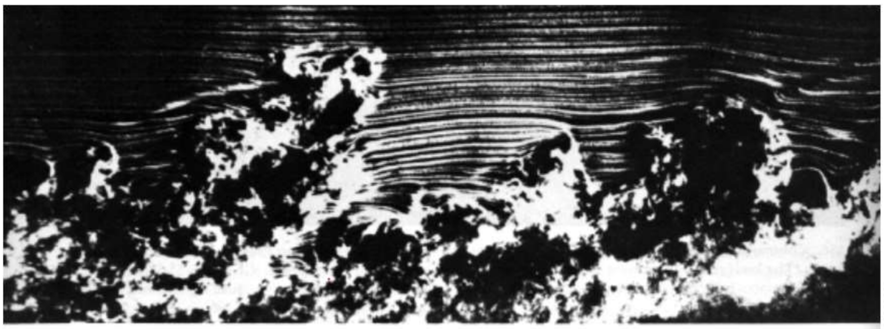
Mechanical Turbulence from Wind Shear





157. Side view of a turbulent boundary layer. Here a turbulent boundary layer develops naturally on a flat plate 3.3 m long suspended in a wind tunnel. Streaklines from a smoke wire near the sharp leading edge are illuminated by a vertical slice of light. The Reynolds number is 3500 based on the momentum thickness. The intermittent nature of the outer part of the layer is evident. *Photograph by Thomas Corke, Y. Guezennec, and Hassan Nagib.*

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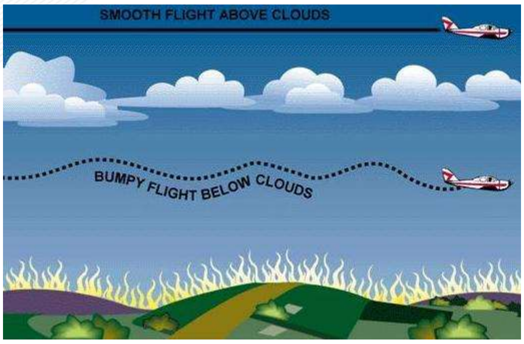
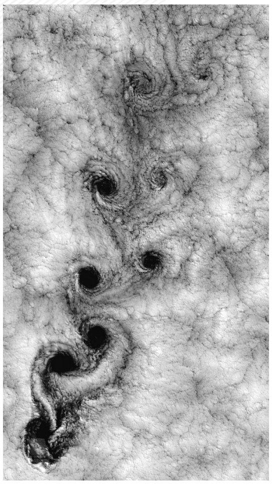
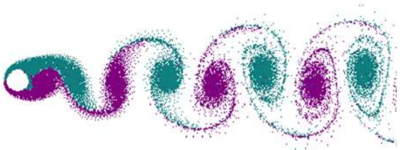
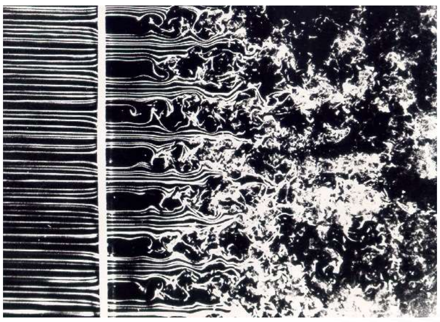
Thermal Turbulence



Mechanical Turbulence from Obstacles

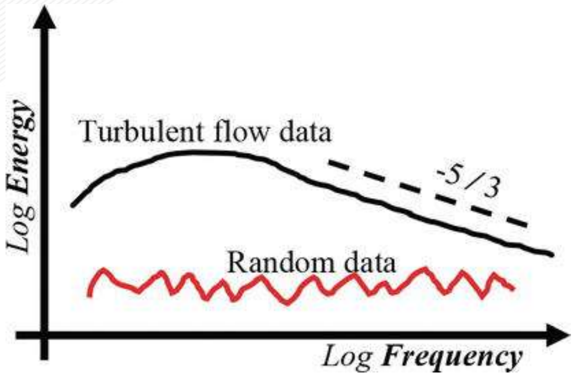


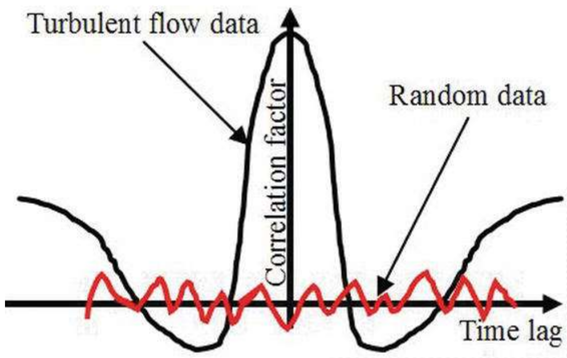




Von Karman Vortex Street

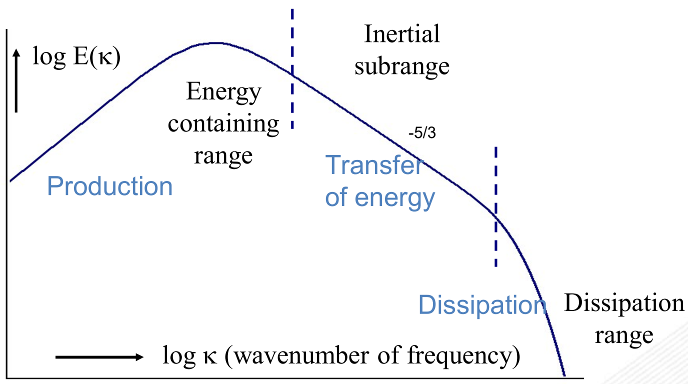
Turbulence… it's, well… randomness… sort of





Frequency Structure of Turbulence

$E(\kappa) = C\varepsilon^{2/3}k^{-5/3}$ Universal spectral shape



Thanks to: A Bakker

Continuity Equation

- What is it?
  - ~~Mathematically~~
  - ~~Verbal Definition~~
  - ~~Assumptions~~
- Why do we care about it?

"Experience of long term flux measurements over tall canopies during the last two decades has revealed that the eddy flux of sensible plus latent heat is typically 30% smaller than the available radiant energy flux. This failure to close the energy balance is less common close to the surface over short roughness but is still sometimes seen, especially in complex topography." – Finnigan et al. 2003

- How do we apply it to EC?
  - Using Reynold's Decomposition

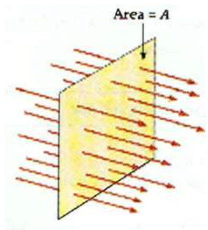
Flux

Understanding the carbon cycle requires many measurements. One of the most important measurements is CO_2 flux.

What is flux?

… the quantity of a substance that moves past a unit area per unit time (e.g., mg/m2/s)

… mean product of a speed (e.g. wind) and density (e.g. CO_2 density).



http://www.ux1.eiu.edu/~cfadd/1360/24Gauss/24Images/Fig24.01.jpg

Flux

Flux is dependant on:

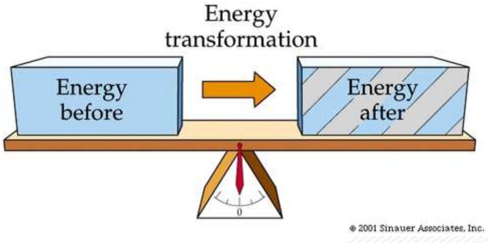
1. Number of properties crossing the area

2. Size of the area of interest begin crossed

3. The time it takes to cross the area of interest

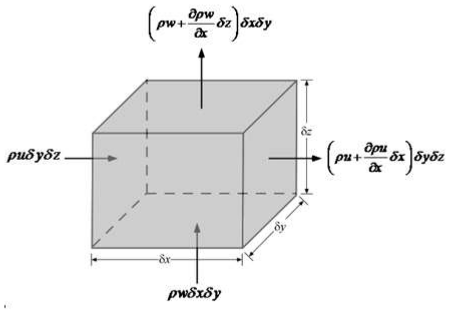
First Law of Thermodynamics

- First law states that energy can neither be created nor destroyed; rather, it can only be transformed or transferred from one form to another.
- Classically, conservation of energy was distinct from conservation of mass; however, special relativity showed that mass is related to energy and vice versa by $E = mc^2$, and science now takes the view that mass-energy as a whole is conserved.



Continuity Equation

$$\frac{\partial \rho}{\partial t} + \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = 0$$



"A hydrodynamical equation that expresses the principle of the conservation of mass in a fluid. It equates the increase in mass in a hypothetical fluid volume to the net flow of mass into the volume." – AMS Definition

Achieving Mass Balance

"Three choices must be made in order to optimize our estimate of terms in the mass balance and thereby our estimate of surface exchange. These are:

1. The averaging procedures that must be applied to the data.
2. The coordinate frame and, as a corollary, the steps we must take to transform measured vector and tensor quantities into this frame.
3. The symmetry we assume for the flow field" (i.e. single point HM3 measurement represents the control volume) – Finnigan et al. 2003

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HM3 Need to explain this better

Hayden Mahan, 8/18/2021

Mass Conservation

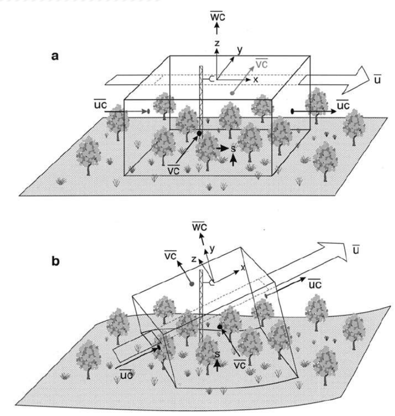


Figure 1. Notional Cartesian control volume over a surface patch. (a) Homogeneous terrain. The coordinate axes are aligned with the mean wind vector which is parallel to the surface as is the lid of the control volume. (b) Complex topography or short averaging period. The *x*-*y* coordinate plane is defined by an ensemble of mean wind vectors and the lid of the control volume is not parallel to the average surface.

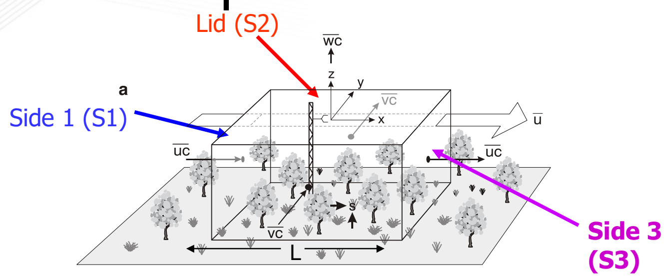
Finnigan et al. 2003

- **Consider a control volume with a source/sink of a substance X.**
- **X can either accumulate/be absorbed (storage) or be transported in/out (advection and turbulence)**

$$NEE = Storage + Transport_{Adv} + Transport_{Turb}$$

change in storage = S(Flux in) – S(Flux out)

Conservation Equation for Control Volume



change in storage = Σ(Flux in) – Σ(Flux out)

$$\int_{dV} \overline{\frac{\partial \chi_c}{\partial t}}\, dV = L^2 \overline{F_c} / \overline{c_d} + \int_{S_1} \overline{u \chi_c}\, dS_1 - \int_{S_2} \overline{w \chi_c}\, dS_2 - \int_{S_3} \overline{u \chi_c}\, dS_3$$

Surface Flux

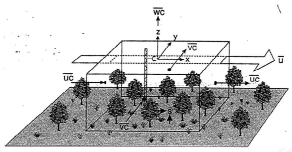
Slide Courtesy of Ray Leuning, CSIRO

- **If we integrate over the control volume, we can mathematically describe the net ecosystem exchange of X as:**

$$\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\overline{S_s}\,dzdydz=\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\left[\overline{\rho_d}\frac{\partial\overline{\chi_s}}{\partial t}+\overline{\rho_d u}\frac{\partial\overline{\chi_s}}{\partial x}+\overline{\rho_d v}\frac{\partial\overline{\chi_s}}{\partial y}+\overline{\rho_d w}\frac{\partial\overline{\chi_s}}{\partial z}+\frac{\partial\overline{\rho_d}\,\overline{u'\chi_s'}}{\partial x}+\frac{\partial\overline{\rho_d}\,\overline{v'\chi_s'}}{\partial y}+\frac{\partial\overline{\rho_d}\,\overline{w'\chi_s'}}{\partial z}\right]dzdydz$$

Storage Term ***Advection Transport*** ***Turbulent Transport***

Where,
h_m = Measurement height
L = Half the length
S_s = Rate of production/depletion
ρ_d = Density of dry air
χ_s = Mixing ratio
u, v, w = Respective x, y, z wind components
' = Fluctuation from the mean
$\overline{\ }$ = Average value of quantity



If we assume a horizontally homogeneous equilibrium layer, we can imply (Finnigan et al., 2003):

- Horizontal gradients are negligible
- Horizontal integration unnecessary
- Measured mixing ratios and turbulent fluxes are representative of the whole volume

Our equation becomes:

Assume $\overline{w}=0$

$$NEE=\int_0^{h_m}\overline{\rho_d}\frac{\partial\overline{\chi_s}}{\partial t}dz+\int_0^{h_m}\overline{\rho_d w}\frac{\partial\overline{\chi_s}}{\partial z}dz+\overline{\rho_d}\,\overline{w'\chi_s'}\Big|_{h_m}$$

0

Eddy Covariance!!!

Concentration profile measurement!!!

Storage Term *Vertical Advection* *Turbulent Transport*

Statistical Parameters to Describe Signal Variation and Co-Variation

- Variance:

  A measure of how a signal varies about its mean.

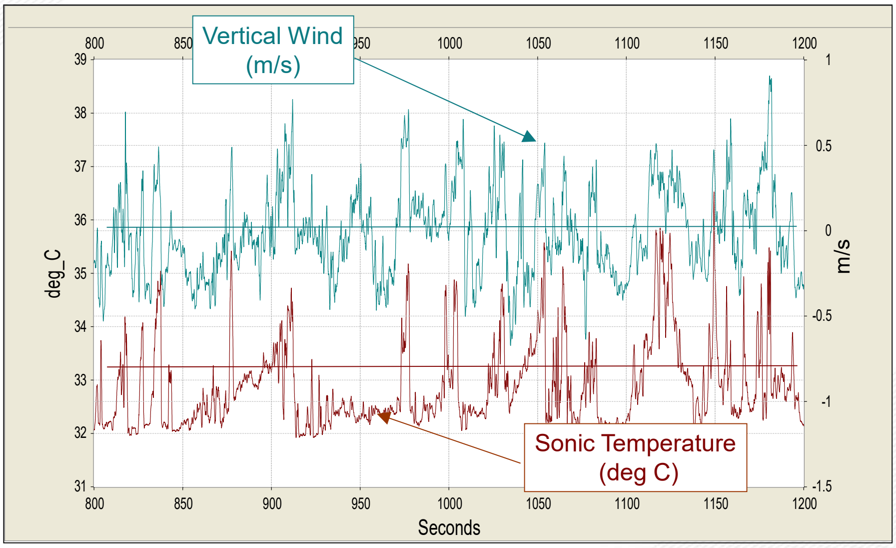
$$Var(x) = \frac{1}{N}\sum_{k=1}^{N}\left[x(k) - \bar{x}\right]^2$$

- Covariance:

  A measure of how two signals vary together about their means.

$$CoVar(x,y) = \frac{1}{N}\sum_{k=1}^{N}\left[x(k) - \bar{x}\right]\left[y(k) - \bar{y}\right]$$

Eddy Covariance Time Series: W and Ts



Reynold's Decomposition

Mean

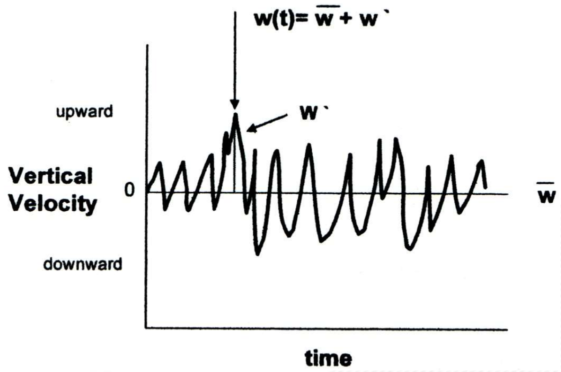
Fluctuation

Horizontal wind $u = \overline{u} + u'$

Vertical wind $w = \overline{w} + w'$

Temperature $T = \overline{T} + T'$

Reynold's decomposition is used to analyze turbulent flow



Reynold's Decomposition

When two variables co-vary together properties associated with Reynolds' averaging rules include:

1. **the mean product of two fluctuating variables is a function of the product of the individual means plus a covariance,** $\overline{xy} = \overline{x}\overline{y} + \overline{x'y'}$
2. **the average of any fluctuating component is zero,** $\overline{x'} = 0$
3. **the average of the sum of two components is additive,** $\overline{x+y} = \overline{x} + \overline{y}$

Reynold's Decomposition

F = ρ_d * w * s

$$F = \overline{(\overline{\rho}_d + \rho'_d)(\overline{w} + w')(\overline{s} + s')}$$

$$F = \overline{(\overline{\rho}_d \overline{w}\overline{s} + \overline{\rho}_d \overline{w} s' + \overline{\rho}_d w' \overline{s} + \overline{\rho}_d w' s' + \rho'_d \overline{w}\overline{s} + \rho'_d \overline{w} s' + \rho'_d w' \overline{s} + \rho'_d w' s')}$$

0 0 0 small small small small

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Reynold's Decomposition

Based on mass flow and Reynolds averaging criteria, the mass and energy flux density between land and the atmosphere using the eddy covariance equation can be defined as:

$$F = \overline{\rho_a} \cdot \overline{w' \cdot s'}$$

Where w is vertical velocity, $\overline{\rho_a}$ is dry air density and s is mixing ratio

Flux densities are considered to be positive for fluxes from the surface to the atmosphere (the atmosphere gains material or energy) and negative for the opposite.

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If these assumptions are satisfied three wind components, temperature, water vapor and CO_2 densities have to be measured at a rate fast enough to collect a statistical representation of wind and scalar.

Fluxes of H, LE, and CO_2 are calculated as:

Sensible Heat $H = \bar{\rho}\, c_p\, \overline{w'T'}$

ρ = mean air density
c_p = specific heat capacity of air

Latent Heat $LE = L\, \overline{w'\rho_v'}$

ρ_v = water vapor density
L = latent heat of vaporization

CO_2 Flux $F_c = \overline{w'\rho_c'}$

ρ_c = CO_2 density

Thank You!

Questions?